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On the Temperature of Sun-spots and the Spectrum of an artificial one. By W. E. Wilson, D.Sc., F.R.S.

The most usual theory of the cause of the darkness of sun-spots is that formulated by De la Rue, Stewart and others, viz. that spots are produced by the down-rush of cooler material on to the photosphere; and the fact most strongly insisted on in support of this theory is that in the spectrum of a spot there are a considerable number of the Fraunhofer lines, both darkened and widened.

The photograph reproduced on Plate 8 of what I have called the "Spectrum of an Artificial Sun-spot," as I believe it will throw a good deal of doubt on the validity of the usual sun-spot theory, and may possibly go towards proving that in sun-spots we have regions of a higher temperature than the surrounding photosphere, and not a cooler one.

The photograph was obtained by the following experiment. An opal globe surrounding an electric arc represented the Sun's photosphere. A small patch of thin paper on the globe, which reduced its light, say, 50 per cent., was my sun-spot. A rectangular glass cell containing nitric oxide fumes was my chromosphere or absorbing layer. A lens was arranged to throw an image of the paper patch on part of the slit of the spectroscope in the same way as a real sun-spot. The photograph of the spectrum shows that where the dark absorption lines cross the band of general absorption due to the paper patch a good many of the lines are both darkened and widened. I find that all lines which have nebulous edges are widened, and lines that have sharp edges, or the sharp edges of bands are not affected. In fact, in this photograph we have an almost similar effect to that of a real sun-spot without having to call in anything like a cool down-rush, but merely by reducing the radiation from the background.

Now what are the causes which give us a dark-line absorption spectrum? In the first place the absorbing gas must be at a lower temperature, but also it must be thick enough to be opaque to those particular wave-lengths which give the positions to its dark lines. As we increase the thickness of the absorbing gas we first get the darkest lines, and then more and more of the lines appear, until ultimately the entire continuous spectrum would be blotted out. This shows that for certain thicknesses of the absorbing gas it is quite transparent to some wave-lengths, but to which ultimately it becomes opaque; and this takes place by no alteration in the temperature. If we have a feeble source of light giving the continuous spectrum, the absorbing layer becomes opaque with a less depth than when the source is of greater brilliancy.

The absorption spectrum of water vapour in the Earth's

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atmosphere is a good example of the effect of increasing thickness on the number of lines seen.

If a sun-spot is a region where the temperature is so high that the solid particles which form the photospheric clouds are turned into a gas, it—being then a bad radiator—would appear comparatively dark. It is of importance to remember that a sun-spot is only dark when compared with the dazzling brilliancy of the photospheric clouds, and is really about as bright as the limelight.

It has been argued that if a spot was a really gaseous region, and that it was deep enough to be opaque, it would radiate as a solid; but I think the suggestion made by the late Professor G. Fitzgerald gets over this difficulty. He said that in the Sun there must be in such a gaseous layer enormous convection currents, which would scatter a lot of the light coming from the lower layers, and in fact that it would never reach the surface, so that the general effect would be the radiation from a layer of gas not deep enough to behave as a solid, so that the spot would appear dark.

There seems to be a good deal of evidence that the Sun's photosphere is merely a rather thin cloud stratum the solid particles of which are carbon. In the first place we do not know any other substance that would remain in the solid form at the temperature of, say, 7000° C.; and from some experiments made by Fitzgerald and myself on the effect of high pressure in the gas surrounding an electric arc we came to the conclusion that carbon at the temperature of 3500° C. in the arc is not nearly at its boiling-point, as was generally supposed.

Another point which greatly strengthens the probability of the photosphere being carbon is the observation made lately by Hale. Using the large solar image of the Yerkes refractor, and placing the slit of the spectroscope tangentially as close as possible to the photosphere, he succeeded in seeing as bright lines both the yellow and green bands of the fluted spectrum of carbon.

This observation is, I think, of first importance in showing that in the photosphere we have carbon.*

That there should be a large quantity of carbon in the Sun also seems probable from the wide determination of it on the Earth. Its atomic weight would also give it a position with other gases that we know occupy this level.

Now is it not conceivable that at a certain distance below the photosphere the temperature may be so high that even carbon is volatilised, and that in a sun-spot we have a local upheaval of this high temperature which volatilises the solid particles of carbon and enables us to see below the photospheric clouds? A spot being then a gaseous layer, it would part with

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* A fluted spectrum was generally considered a very low-temperature one, but Hale's observation shows that carbon gives such a spectrum at a temperature of at least 7000° C., or twice the temperature of the arc.

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its heat much slower than the photosphere, and thus have its life prolonged.

It has been urged that, even if the solar temperature was raised enough to volatilise the photospheric clouds, they would merely reform again at a greater altitude where the temperature was lower; but it is easy to see that the carbon vapour could not reach a sufficient altitude to reform into a cloud layer. If this was so we would have cloud layers formed at suitable altitudes of iron, titanium, magnesium, and many others; and the fact that these do not exist is, I think, a proof that carbon also, with a suitable rise of temperature, would be unable to remain in the solid form.

It therefore seems that brilliancy *per se* is no criterion as to the temperature of a star, and if the solar temperature was raised a certain amount his brilliancy would fall probably 50 per cent., his spectrum would show a considerable number of the lines of calcium, magnesium, and others as bright lines, while the lines of substances like titanium and vanadium, which lie below the photosphere, and the bands of carbon would be darkened and widened. In fact, the solar spectrum would become almost identical to that of IV. type stars, which should therefore be classed as hotter and not cooler than the Sun.

Professor Hale has pointed out lately that the spectrum of these stars is almost identical with that of a sun-spot.

Mr. W. M. Mitchell has recorded in the *Astrophysical Journal*, 1904 June, that out of 270 lines affected in some spots which he observed during March and April sixty-eight were reversed. Now why should we see lines reversed in spots? Certainly not by the supposed down-rush of cool material, but possibly by want of radiation from the layer giving the continuous spectrum, or by a very high temperature of the gas giving the line spectrum. By the first cause we can see the hydrogen lines bright on the Sun's limb, when we then have as a background the feeble spectrum of the lower corona. If the radiation from the umbra of a spot was as feeble as the corona close to the Sun's limb, then we should see the hydrogen lines as bright as we do in a prominence.

In the Sun there seems to be two distinct layers which give us a continuous spectrum: first, the photospheric clouds; and secondly, at some depth below them, a layer of gases of sufficient thickness and pressure to be opaque. Between these two layers lie the vapours of titanium, vanadium, and other elements of suitable atomic weight. Below this gaseous layer probably lie the elements like uranium with high atomic weight; and unless they are occasionally pushed up by convection currents, their spectrum will never be seen.

As we approach the photosphere probably the vapour of all or most of the elements that lie beneath it and above the gaseous layer get mixed up and carried above it, and thus give us the ordinary Fraunhofer spectrum. It is this mixed layer of hot

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gases that gives us the flash, and it evidently cannot rise much above the photosphere. In a sun-spot then the causes which give rise to the widening and darkening of some of the lines is partially due to the want of brilliancy of the gaseous layer below, and also to the greater depth of the absorbing vapours of the elements like titanium, &c., whose atomic weight gives them a place between the photosphere and the gaseous layer. The photospheric clouds seem to be not thick enough to be quite opaque, and a certain amount of light breaks through by the pores from the gaseous layer below. This helps to make the Fraunhofer lines darker than they would be if the photosphere was quite opaque to light coming from below. If the photosphere was of sufficient depth to be quite opaque, and also if the vapours of the elements lying below it could not reach the surface by convection currents, then only elements like hydrogen with a lighter atomic weight than twelve of carbon could lie above it, and we would get a spectrum like that of *Sirius*. As there would be only a few dark lines of hydrogen to absorb the light of the continuous spectrum the brilliancy of the star would be greatly enhanced principally in the violet end. This would not suggest, as Sir N. Lockyer urges, a higher temperature than the Sun, but one slightly cooler and not so near the critical temperature at which carbon can exist in the solid form.

Langenbach has shown that in a bright line spectrum as the temperature rises the maximum intensity shifts towards the violet end. Campbell finds that the Wolf-Rayet star D.M. + 30°3639 has an extensive hydrogen atmosphere, and that Hα is very faint, while Hγ is brighter, and Hβ very much brighter. This seems an interesting point in favour of the very high temperature of this class of stars.

As a summary of this paper I maintain that in the Sun, and also in stars of the same or lower temperature, we have two distinct layers which give us a continuous spectrum. First, a gaseous one of high temperature and pressure; and secondly, a layer of carbon clouds which are a far greater radiator than the first gaseous layer. In sun-spots where the temperature is locally high enough to volatilise the carbon clouds we get radiation from the gaseous layer alone and the absorption spectrum much intensified by those vapours which lie between these two layers. In stars like *Sirius* we get the spectrum due to a much greater depth of carbon clouds than we have in the Sun, and outside of which we have principally a great atmosphere of hydrogen. In IV. type and Wolf-Rayet stars we have bodies at too high a temperature for carbon clouds to form, and we have the continuous spectrum only from the gaseous layer, which is darkened also by the powerful absorption spectrum of carbon, titanium, and other elements with which the stars' atmosphere is charged.